Accelerators for Proton Therapy

Inoue, Makoto; Iwashita, Yoshihisa; Noda, Akira

Bull. Inst. Chem. Res., Kyoto Univ., Vol. 69, No. 1, 1991.

Note

Accelerators for Proton Therapy

Makoto INOUE, Yoshihisa IWASHITA and Akira NODA

Received February 9, 1991

Various kinds of accelerators for proton therapy proposed at many places including Kyoto University are compared. In many cases the compact machines have their own difficulties. Large magnet of cyclotron, large RF power source of linac and complex system of synchrotron are examples of such difficulties.

KEY WORD: Cyclotron/Linac/Synchrotron

1. INTRODUCTION

Particle accelerators have been developed to study structures and interactions of fundamental particles in the fields of nuclear physics and elementary particle physics. Some of these accelerators have been also used for medical therapy. John Lawrence treated a few cancer patients with neutrons in 1930s with his brother Ernest Lawrence who developed the cyclotron. At Harvard Cyclotron Laboratory, proton therapy has been made since 1959. In Japan, pioneer works of both proton and neutron therapy with a cyclotron have begun at National Institute of Radiological Science(NIRS). More advanced proton therapy has been made at the Particle Radiation Medical Science Center(PARMS) of the University of Tsukuba using a proton beam from the booster synchrotron of National Laboratory for High Energy Physics(KEK). Heavy ion therapy and meson therapy have been also tried at Berkeley and at three meson factories, LAMPF, TRIUMF, PSI(SIN).

These experiences show that the particle beam therapy is very promising to control tumors. Thus many physicians come to desire to have dedicated machines for cancer therapy. The first dedicated heavy ion therapy accelerator is now under construction at NIRS, Chiba. EULIMA project of heavy ion therapy is proposed by European countries. Once PIGMI, linear accelerator designed for meson therapy machine, was proposed but now no dedicated meson therapy project is promoted.

On the other hand, many dedicated proton therapy projects are proposed all over the world. The proton facility is less expensive than the heavy ion or meson facility. The first treatment recently has begun at Loma Linda University with a dedicated small proton synchrotron. This synchrotron was developed at Fermi National Accelerator Laboratory(FNAL).

At Kyoto University, an accelerator facility has been proposed for multidisci-

井上 信, 岩下 芳久, 野田 章: Nuclear Science Research Facility, ICR, Kyoto University, Uji, Kyoto 611, Japan

plinary use including proton therapy and meson therapy, but it is very difficult to be funded. Thus we are considering to realize a proton therapy machine in the first place. A 7 MeV proton linac which has been developed at Nuclear Science Research Facility of ICR to study the future project of the meson facility, may be suitable for an injector of a proton therapy synchrotron.

Some other groups propose the compact cyclotron version, superconducting synchrocyclotron version, linac version and H^- synchrotron version. Comparisons of these proton therapy accelerators are made in the following sections.

2. CYCLOTRON AND SYNCHROCYCLOTRON

The energy of the proton beam for cancer therapy is 70MeV to 250MeV depending on the location of tumors. A 70MeV cyclotron is now commercially available but a 250MeV cyclotron becomes large and expensive. Therefore multi-purpose cyclotrons are constructed so far though the 160MeV Harvard synchrocyclotron is now used mainly for proton therapy. Two such examples of new facilities under construction for proton therapy are a 200MeV separated sector cyclotron at NAC, South Africa and a parasite use of the 590MeV ring cyclotron at PSI, Switzerland. The medical program is the most important at NAC. The PSI cyclotron accelerates only 590MeV protons. Therefore it is able to deliver simultaneously the proton beams to both medical use and any other experiments by splitting the extracted beam of the cyclotron.

On the other hand, a dedicated low cost cyclotron has been recently proposed by IBA, Belgium company[1]. The main characteristics of the proposed cyclotron are listed in Table 1. This cyclotron is a fixed energy cyclotron so that an energy degrader is necessary to change the beam energy at a patient. The unique feature of this cyclotron is very high magnetic field using the room temperature magnet. The IBA compact 230MeV cyclotron seems to be one of the goals of the dedicated machine, but there are some difficult problems to be solved.

1. Minimum hill gap (6 mm) is very small. Field adjustment mechanism should be considered because it is rather difficult to keep field accuracy of order of 10^{-4} at such small gap.
2. Maximum magnetic field is so high that saturation at the edge of the sector on the pole tip should be carefully studied.
3. Small turn separation causes damage on the septum of the beam extraction system. Maintenance of the extraction system in the compact cyclotron is not easy unless the technician receives much radiation exposure.

A synchrocyclotron with supercoducting coils is another option of the cyclotron version. H.G.Blosser proposed a compact superconducting synchrocyclotron[2]. Sumitomo Heavy Industry Co.,Ltd. has also studied to design a 230MeV superconducting synchrocyclotron[3]. The unique feature of the Sumitomo machine is the followings. The average magnetic field is 3.3T and the weight of the magnet is 180 tons. They use 3-sector shims to increase focusing strength though the field is not isochronous. The 3rd-harmonic re-entrant type accelerating cavities are situated at the magnet gap and capacitively coupled with four ferrite-contained small cavities located out side of the

Table 1. IBA-CYCLONE230-PARAMETERS

Beam			
type of ions		H^+	
energy (fixed)		230	MeV
maximum intensity	-guaranteed	25	nA
	-design value	100	nA
emittance of the extracted beam			
	-horizontally	<15	π.mm.mrad
	-vertically	<10	π.mm.mrad
energy spread		<0.3	per cent
Power consumption			
Beam on target		350	kW
Stand-by 1	(magnet and vacuum)	250	kW
Stand-by 2	(vacuum only)	25	kW
Magnetic structure			
number of sectors		4	
sector angle (radially varying)		36-53	degrees
sector spiral angle (radially varying)		0-60	degrees
hill field at extraction		3.09	Tesla
valley field at extraction		0.98	Tesla
D.C. power in the coils		190	kW
iron weight		165	tons
copper weight		26.6	tons
R.F. system			
number of dees (connected at the center)		2	
dee angle (radially varying)		45-30	degrees
harmonic mode		4	
frequency (fixed)		102.11	MHz
dee voltage (nominal)		100	kV
estimated dissipated R.F. power	-per dee	30	kW
	-total	65	kW
Ion source			
type of source (external)		hot filament P.I.G.	
filament power		1.5	kW
filament lifetime		>800	hours
time for filament changing			<30 min.
arc power		0.5	kW
H_2 flow rate		3…5	st cc/min
rise/fall time		15	microsec.

magnet for frequency modulation. The 3/3 resonant extraction method is adopted.

A coupled resonance to lose the beam may occur before extraction. The good balance of four small cavities for frequency modulation is important for stable acceleration of the beam. More careful study is needed.

3. LINAC

The linear accelerator is usually constructed to get high intensity beam and is expensive. But if the low intensity beam is enough, it is able to make a low cost machine. For example, the first stage of the system is an RFQ section operated at the frequency of 433 MHz and the second stage is the Alvarez section operated at the frequency of 433 MHz and 1300 MHz. The characteristics of the example of our preliminary design is listed in Table 2. A conceptual design of the 1300 MHz cavity is shown in Fig. 1. The very small duty factor makes it low power consumption. At Los Alamos, a similar design is considered[4].

The cooling of the cavities is important in these compact linacs. Another problem is the large volume of the RF power source. Development of the compact RF source is necessary. We are expecting that the high power Klystrode is a hopeful candidate. The radiation damage of permanent quadrupole magnet in the drift tube should be considered at higher energy sections. The focusing magnet can be installed only between tanks at 1300 MHz sections.

Table 2 Main characteristics of a 250 Mev proton linac[5]

cavity length	RFQ	DTL-1	DTL-2
cavity length	2m	7m	36m
RF frequency	433 MHz	433 MHz	1300 MHz
accel. field E_0		6 MV/m	9 MV/m
transit time factor		0.8	0.8
synchronous phase		30°	30°

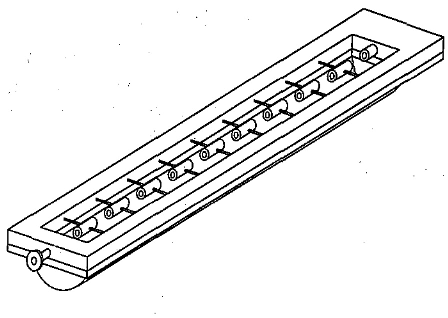

Fig. 1. a conceptual drawing of the 1300MHz DTL cavity.

4. SYNCHROTRON

The synchrotron is easy to change the energy of the beam and less expensive than a variable energy cyclotron. But the system of the synchrotron is a little complicated. It contains an injector, a main ring composed of many dipole and quadrupole magnets and an injection and extraction system. The proton synchrotron constructed at Loma Linda University Hospital shows typical compactness of the system. The injector is a 2MeV RFQ linac situated above the synchrotron ring which is four-fold symmetric and composed of eight dipole magnets with edge focusing. The main parameters are listed in Table 3. It is very compact but the beam intensity does not yet reach the design value. It may be limited by large dispersion and chromaticity of the lattice because the beam from the RFQ linac has rather large energy spread. The main ring has no adjustable element of the sextupole field. Higher order correction of the magnetic field

Table 3 Loma Linda Synchrotron parameters

Injection energy	2.0 MeV
Extraction energy	70-250 MeV
Bending radius	1.6 m
Number of sectors	4
Long straight section	4×2.0 m
Short straight section	4×0.5 m
Circumference of ring	20.053 m
Number of ring dipoles	8
Injection field	0.128T
Extraction field	0.77-1.52T
Focusing	Edge-angle weak focusing
Ion Source	p duoplasmatron
Injector	425 MHz RFQ
Injection beam current	30 mA
Injection	Single turn, vertical electric kicker
Synchrotron RF harmonic number	1
Synchrotron RF frequency	0.975-9.17 MHz
Acceleration time 2-250 MeV	0.5 sec
Energy gain per turn	90 eV
Peak RF voltage	330 V
Cavity structure	Untuned ferrite load re-entrant cylinder
Extraction	Half-integer resonant extraction with electrostatic wire septum and Lambertson iron septum
Energy (variable pulse-to-pulse)	70-250 MeV
Energy spread	$\pm10^{-3}$
Intensity	1×10^{11}ppp
Basic spill time	1 sec
Spill uniformity	$\pm2.5\%$
Spill rate dynamic range	10^{10}-10^{12} protons/sec

seems to be important in the small ring because portion of the fringing field becomes larger comparing with a big accelerator[6]. The beam transport system is relatively large. Therefore a little larger synchrotron containing the adjustable elements is permissible. The University of Tsukuba has proposed a six-fold symmetric lattice with strong focusing. The main parameters are listed in Table 4. The EULIMA has also proposed a synchrotron version as listed in Table 5.

Table 4 Tsukuba 230-MeV synchrotron

Lattice		
Circumference	34.939	m
Superperiod	6	
Structure	DOFB	
Long Straight Section	3.0	m
Bending Radius	1.55	m
Bending Magnet Length	1.623	m
Horizontal Tune	1.8	
Vertical Tune	1.85	
Horizontal β	1.836-6.439	
Vertical β	1.684-6.955	
Maximum Dispersion	2.6	m
γ at Transition	1.56	
Bending Magnet		
Injection(10MeV)	0.296	T
Extraction(230MeV)	1.498	T
Deflection Angle	60	deg
Edge Angle	30	deg
Gap	6.5	cm
Width	28	cm
Quadrupole Magnet		
Aperture	11.6	cm
Length	20	cm
Field Gradient(F)	5.9483	T/m
Field Gradient(D)	1.1416	T/m
Radiofrequency Acceleration(10-230MeV)		
Frequency Range	1.24-5.11	MHz
Voltage	450-300	V
Stable Phase	20-30	deg
Repetition Rate	0.5-1	Hz
Injector: Linac		
Ion Source	Multicusp H^-	
RF Frequency	425	MHz
Input Energy	30	keV
Output Energy	10	MeV
RMS Normalized Emittance	0.01	πcm-mrad

Table 5　EULIMA synchrotron

Energy range	100-450MeV/n
Circumference	60m
Structure	FODO
8 Bending magnets	$B_{max}=1.2T$
18 Q-poles magnets	$G_{max}=10.T/m$
Ion source	ECR
Injection energy	2-5MeV/n(RFQ or linac)
Acceleration	f=0.5-4MHz V=10kV
Ejection spill	0.5-1s,1/3 integer resonance ultra slow ejection

Table 6　Main Parameters of Medical Proton Synchrotron

Energy Region		
Injection	7	MeV
Extraction	100—250	MeV
Repetition Rate	0.5	Hz
Circumference	33.526	m
Focusing Structure	FBDBFO	
Length of Long Straight Section	3.0	m
Number of Betatron Oscillations		
Horizontal Direction	1.75	
Vertical Direction	1.25	
Transition Energy	765	MeV
Bending Magnet(Without Edge Focusing)		
Radius of Curvature	2.025	m
Length along the beam orbit	1.591	m
Bending Angle	45	Deg.
Field Strength		
Maximum (at 250MeV)	1.20	T
Injection (at 7MeV)	0.19	T
Quadrupole Magnet		
Length	0.20	m
Maximum Field Gradient (QF)	2.46	T/m
(QD)	5.51	T/m
RF Acceleration System		
Frequency Range	1.087—5.491	MHz
Cavity	Ferrite Loaded Untuned Re-entrant Cavity	
Energy Gain per Turn	137	eV
Peak RF Voltage	400	V
Acceleration Time	0.5	s
Scheme of Extraction	1/3	Resonance
Beam Spill Time	0.95	s
Beam Intensity	7×10^{10}	ppp

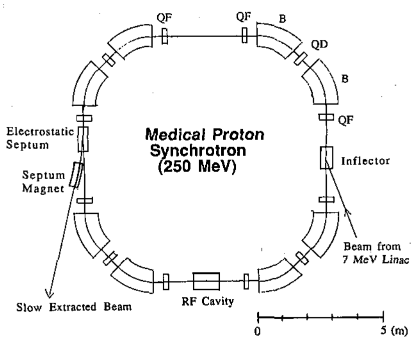

Fig. 2. an example of the proton synchrotron lattice.

ACCTEK Associates has recently developed prototype magnets and vacuum chambers for a synchrotron dedicated for therapy which accelerates H^- ions[7]. A weak field of 5.6kG at peak and good vacuum of 10^{-10} Torr are necessary to accelerate H^- ions up to 250MeV, which causes a relatively large ring diameter of 13.7m. A similar H^- synchrotron for therapy is also proposed at Moscow[8]. The main advantage of the H^- synchrotron is an easy extraction of the beam using a stripping foil. And the extracted beams are delivered simultaneously to several beam courses. Moreover the emittance of the extracted beam becomes small and the intensity of the extracted beam can be monitored and therefore stabilized by measuring the current of the electrons stripped from the H^- ions[8].

At Kyoto University we are considering the compact proton synchrotron for therapy as mentioned above. We are now testing a 7MeV linac which can be an injector. As for the synchrotron ring some different lattices are being examined by computer analyses. An edge focusing ring with small correction quadrupole magnets has moderate size of betatron function but large dispersion and large change of lattice properties due to mis-alignment of the magnets comparing with a strong focusing ring[9]. A similar comparison is done by KEK-Tsukuba group[10]. One of the examples of our studied lattice is shown in Fig. 2 and main parameters are listed in Table 6.

5. CONCLUSION

Many accelerators for proton therapy have been proposed. The first one has been constructed at Loma Linda University, but the synchrotron version should be improved. For example, an injector, focusing strength, chromaticity correction and so on. A compact isochronous cycrotron proposed by IBA is very attractive comparing with a superconducting synchrocyclotron but it is still necessary to verify the feasibility of construction of such high quality magnet. A compact linac is good for beam spill but it is a little long and still may be expensive.

A combination of a high intensity linac and a small dedicated synchrotron ring may be a candidate of our case. We need a neutron source and a meson source if possible in the future. The high intensity injector can be extended to higher energy and/or followed by a rapid cycling synchrotron. We will continue the development of a high performance linac and a compact synchrotron.

REFERENCES

(1) Y. Jongen, A. Laisne, G. Lannoye, publication of the Ion Beam Applications s.a.(IBA), May 1990.

(2) H.G. Blosser, Proceedings of Particle Accelerator Conf., Washington DC, 1987,BAPS 32, 171, (1987).

(3) T. Takayama, private communications.

(4) G.P. Lawrence et al, paper presented at PTCOG 13, LBL, Berkeley, California, November, 1990.

(5) Y. Iwashita, unpublished engineering note (1986).

(6) S. Fukumoto, private communications.

(7) R.L. Martin, proceedings of the 2nd European Particle Accelerator Conference, Nice, June 1990, s103, (1990).

(8) V. Khoroshkov, L. Goldin, K. Onosovski and G. Klenov, paper presented at PTCOG 13, LBL, Berkeley, California, November, 1990.

(9) Y. Miyauchi, engineering note, collaboration between IHI and Kyoto University, unpublished (1991).

(10) K. Endo et al, KEK preprint 90-50 June 1990 A.